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LONG-TERM STUDIES WITH THE ARIEL 5 ASM.
II. THE STRONG CYGNUS SOURCES

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ABSTRACT

The three bright 3-6 keV X-ray sources in Cygnus are examined for regular temporal variability with a 1300-day record from the Ariel 5 All Sky Monitor. The only periods consistently observed are 5.6 days for Cyg X-1, 11.23 days for Cyg X-2, and 4.8 hours for Cyg X-3. The 78.4-day period of Kemp, Herman and Barbour (1978) for Cyg X-1, the 9.843-day period of Cowley, Crampton and Hutchings (1979) for Cyg X-2, and the 16.75-d period of Holt et al. (1976) for Cyg X-3 are not confirmed.

Subject Headings: X-rays: binaries -- X-rays: sources

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I. INTRODUCTION

We have previously reported periodic modulation in the intensities of all three of the bright X-ray sources in Cygnus, based upon analyses of the first year of data obtained with the Ariel 5 All-Sky Monitor (ASM). The data base has since grown to 1300 days, so that we can now test for the presence of these effects over a temporal record which is approximately four times longer. Detailed descriptions of the experiment and data reduction algorithms are given by Holt (1976) and Kaluzienski (1977), respectively, while examples of the analysis techniques applied to the long-term ASM data bases of known periodic sources may be found in Holt et al. (1979).

The 1300-d records of all three Cygnus sources are displayed in Figure 1, modified by all of the corrections which the automated computer algorithms are capable of applying. There are some obvious examples of contamination which have eluded this procedure, c.f. the synchronous increases in all three sources ca. day 1440 and the erratic high points in the Cyg X-3 record during the extended high state of Cyg X-1. We have removed, from further analysis, a total of approximately 40 days of data during which time there may have been some systematic solar contamination of the record owing to the proximity of the sun (in spacecraft longitude) to the Cygnus sources; these data were removed via this geometry condition only, and <u>not</u> by visual inspection of the record for potentially contaminated data. The only data which were <u>subjectively</u> removed were all the Cyg X-3 data taken during the prolonged Cyg X-1 high state. As sources closer than $\sim 10^0$ may sometimes be confused by the ASM, the

data base uses the maximum value which a source may have in order that transient episodes of increased emission are not missed; this means that some values of Cyg X-1 and Cyg X-3 data are systematically high. As we are concerned here with possible periodic modulation of the source intensities, we have assumed that contamination from neighboring sources (and from other systematic effects) will be asynchronous with such inherent modulation if the data base is long enough. A demonstration of the general soundness of this approach to the analysis of the ASM data base may be found in Holt et al. (1979), where we were able to extract known periodicities from weaker sources in more highly confused regions of the X-ray sky.

II. CYG X-1 DATA ANALYSES

Our initial report of 5.6-d modulation of the Cyg X-1 intensity (Holt et al. 1976a) was for the initial $\sim$ 300 days of Figure 1. We can now report that the modulation persists throughout the entire 1300 days, with the possible exception of the "high state" data intervals. The "high state" data were displayed on a cycle-by-cycle basis by Holt et al. (1976b), with an indication that relative minima systematically appeared at HDE226868 superior conjunction. Nevertheless, folding all of the "high state" data at 5.6-d does not yield a significant minimum at this phase; this apparent lack of net 5.6-d synchronization may possibly be ascribable to the very large ($\sim$ factor of 4) asynchronous variations over a relatively limited number of 5.6-d cycles.

We have divided the remainder of the Cyg X-1 record (excluding only the two unambiguous "high state" episodes) into eleven intervals

of 1-3 month duration, using natural gaps in the data record and visual inspection of Figure 1 to arrive at boundaries between which Cyg X-1 may be relatively well-characterized by an average value. For all of these eleven intervals, we folded the data in six bins using the HDE226868 ephemeris of Bolton (1975) with one bin centered at superior conjunction. In seven out of the eleven cases, that bin was the one with minimum intensity of the six. In the remaining four cases, that bin was second lowest three times and third lowest once (and was always statistically consistent with being lowest). The a priori probability of obtaining any distribution of the eleven trials which has at least seven minimum occurrences, no more than one occurrence of the third lowest, and no occurrences of the three highest, is 5×10^{-5}. The eleven trial intervals were then coalesced into two groups: one with relatively high average value (approximately 450 days of non-contiguous coverage), and the other with relatively low average value (approximately 650 days). No attempt was made to remove trends: the data were simply sorted into the six 5.6-d bins and a weighted average of all the data in each bin was computed. These two independent 5.6-d light curves are displayed in Figure 2, along with the overall light curve for all eleven intervals (i.e. the weighted average of the two other traces).

For the high-average and low-average light curves, the minima at HDE 226868 superior conjunction relative to the overall average for the six bins are significant at the 2.8 and 2.3 sigma levels, respectively. For the overall light curve, the statistical significance is 3.4 sigma. This significance is based entirely on the errors assigned to the individual data points, which are (typically) inflated by $\sim$ 30% over statistics

to accommodate contributions from systematic effects which are not directly measurable. If we were to use, instead, the scatter of the six bins about their mean in the overall light curve to estimate the "effective" statistical error, the significance of the decrement at superior conjunction would be reduced by almost a factor of two (which suggests that there are still some systematic effects which cannot be properly corrected). Nowhere in the above have we imposed the argument that we expect the 5.6-day effect, if real, to be <u>in phase</u> with superior conjunction. Perhaps the most direct way to make this adjustment is to consider the intensity in the bin centered at superior conjunction against the average of the other five (rather than all six); in that case, the decrement at conjunction is significant at the 4.1 sigma level (using the estimated data errors to compute the bin errors), or 3.1 sigma (using the scatter of the remaining five bins about their mean). Note that this decrement represents only $\sim$ 1% of the total area under the 5.6-day light curve. As there is no corresponding minimum at inferior conjunction, we find no evidence for a fundamental periodicity of 2.8-days rather than 5.6-days.

We could not have "discovered" the 5.6-d periodicity of Cyg X-1 without previous knowledge of both the period and the phase; the 5.6-d modulation is not detected with any statistical significance in a Fast-Fourier transform of the data displayed in Figure 1. It is true that we achieve a local maximum at 5.6-d for χ^2 as a function of trial period (against the hypothesis of a constant source intensity), but there are many such peaks with even greater formal statistical significance at much longer periods. We consider the phase consistency, therefore, to

be crucial to the identification of the effect we observed with a true periodicity in the X-ray source. All other pseudoperiodicities in our record are presumed to reflect the Fourier decomposition of a distinctly variable emission history.

Kemp, Herman and Barbour (1978) have detected a 78.4 periodicity in the first 1100 days of the data in Figure 1, which apparently correlates with other photometric and polarimetric data of Cyg X-1. Applying exactly the same data selection and correction criteria as we have for the 5.6-d effect discussed above (but not the same as used by Kemp et al. 1978), we are unable to detect any significant modulation at this period. The FFT and χ^2-vs.-trial-period analyses which we perform routinely each, in fact, yield local minima at 78.4-days. The overall 78.4-day light curve can be fit with a modulation of amplitude $\sim$ 3.5% (at a phase within 10% of that reported by Kemp et al.), but we can detect modulation which is formally much more significant at periods > 5 days removed from 78.4 days. As discussed briefly above, we have no reason to assume that these period candidates represent true modulation of the source intensity. We can not exclude a 78.4 day modulation with amplitude $\lesssim$ 5%, but we can not detect it, either.

III. CYG X-2 DATA ANALYSES

Holt et al. (1976c) reported a periodicity of 11.17$\pm$.10d in the first 400 days of Cyg X-2 data displayed in Figure 1, with an amplitude of $\sim$ 10%. This periodicity could be independently detected in later samples of the data, as well. A synopsis of the new evidence for the presence of the effect is displayed in Figure 3. The best-fit period

to all of the data is 11.23$\pm$.03d, and the best-fit sinusoidal amplitude of the modulation is 7.2%, although it can be slightly better-fit by a saw-tooth form than by a sinuosoid. An autocorrelation function was constructed as a diagnostic tool, wherein the data were grouped in one-day bins (characterized by the weighted average and assigned error of all data in that bin), with days during which there was no data given the average source value (and an assigned error of three times that value). The autocovariances were then computed by weighting each bin using the assigned errors, so that the "best" data contributed most and the artifically-filled bins virtually nothing. This autocorrellagram is displayed to demonstrate that multiples of 11.23-d are discernible, and that overall variations in Cyg X-2 intensity typically occur over $\sim$ 50 day intervals.

IV. CYG X-3 DATA ANALYSIS

The finest temporal resolution available from the ASM is $\sim$ 100 minutes, or $\sim$ 1/3 of the well-known 4.8-h variation of Cyg X-3. Nevertheless, the lack of sharp intensity gradients in this variation allows us to consistently detect the modulation by tagging each measurement with the time of the middle of the data accumulation interval, and folding as in the Cyg X-1 and Cyg X-2 examples above (with the data added to only the bin into which the mid-time of the observation falls). Even though each measurement actually extends over several light curve bins, Figure 4 indicates that the asynchronous sampling allows us to achieve a reasonable measure of the light curve. We attempted to search for dependence of the light curve shape on average intensity, but could not detect any statistically significant variations. Plotted in Figure 4

are the high-average, low-average and overall 4.8-h light curves (exactly as was done for Cyg X-1 in Figure 2). For a variety of average intensity values between 0.1 and 0.7 (not shown explicitly in Figure 4), we always achieved statistical consistency with the three parameters which characterize the overall average curve: a minimum centered in bin 1, a maximum in bin 10 (phase 0.62 $\pm$ .03 relative to the center of bin 1), and a maximum-to-minimum-bin ratio of 1.87 $\pm$ .14. While we are not able to comment on the shape of the 4.8-h variation for any individual cycle, it would appear that the above three parameters are not strongly dependent on the local source intensity on the average. While our sampling constraints clearly force our value of the maximum-to-minimum-bin ratio to represent a lower limit, a systematic variation in this ratio as a function of average intensity could have important consequences in model determinations. We do observe a slightly decreasing ratio with increasing intensity, but the individual ratio errors exceed the deviations from average.

We have previously reported a period of 16.75$\pm$.25-d from the first 400 days of Figure 1, along with independent confirmatory data over $\sim$ 3 cycles from the Ariel 5 SSI experiment during which there was no ASM coverage (Holt et al. 1976d). The present data indicate that the actual period may be 33.0$\pm$0.2d, as demonstrated in Figure 5. The χ^2-peak is not impressive, but the coincidence of several pieces of evidence is consistent with this conclusion. The high-average 33.0-d trace has considerable overlap with that used to find the originally-reported 16.75-d effect; clearly, this trace can be reasonably well-fit with two

similar cycles over $\sim$ 33.0-d. The low-average trace, which is a completely independent data sample, also exhibits two peaks, but their separation is clearly not equal to half of 33.0-d. An autocorrelation for all the Cyg X-3 data, which is computed in a manner similar to that displayed in Figure 3 for Cyg X-2, suggests the reproducability of a 33.0-d light curve: in the autocorrellagram of Figure 5, we have indicated the positions of expected features for two peaks separated by $\sim$ 10-d in a 33-d cycle. Lastly, the completely independent Ariel-5 SSI data which were approximately in phase with the 16.75-d ASM ephemeris agree even more closely with the presently reported 33.0-d ephemeris.

V. DISCUSSION

a. Cyg X-1

The 1300-d light curve of Cyg X-1 exhibits rather less variability on timescales less than $\sim$ 1 month than do those of Cyg X-2 and Cyg X-3. Aside from the dramatic high-state episodes commencing near days 480 and 670, there are few significant short-term variations. The largest short-term increase (near day 610) is definitely real, as it was also observed from SAS-3 (Canizares et al. 1976), but the small number of others (such as that near day 1440) may arise from ASM systematics. Otherwise the data are generally consistent with a bimodal source intensity which, in the low-state, is characterized by gradual monotonic variations extending over months. No convincing evidence for true periodicity in this long-term variation could be found.

The persistent 5.6-d modulation almost certainly has its origin in the increased line-of-sight gas column density near HDE226868 superior

conjunction which is manifested most strikingly in "absorption dips" (cf. Murdin 1976). If we assume that the absorption arises from cold gas, the present results indicate that the average increased column density encountered near superior conjunction corresponds to $\sim 10^{22}$ H-atoms/cm^2.

b. Cyg X-2

We observe a modulation of the Cyg X-2 intensity with a period of 11.23 $\pm$ .03 days. Other candidate periods which have been previously reported for Cyg X-2 or its optical counterpart V1341 Cyg (all photometric) are 13.6-d (Chevalier et al. 1975), 0.92-d (Wright et al. 1976) and 5.9-d (Basko 1977). We find no evidence for any of these candidate periods in the ASM data. The many X-ray and optical similarities between Sco X-1 and Cyg X-2 suggest that timescales in excess of a few days might not appear to be likely associations with a binary period, as the Sco X-1 binary nature is now well-established with a period 0.787 days (Gottlieb, Wright and Liller 1975; Crampton and Cowley 1975). New evidence for a <u>spectroscopic</u> period of 9.843 days (Cowley, Crampton and Hutchings 1979), further complicates the picture. We find no evidence for a 9.843 day modulation in the ASM data, but we appreciate that a spectroscopic period is less ambiguously interpretable in terms of a binary system than are photometric periods.

The origin of the 11.23 day effect we measure is considerably less straightforward. It would be reassuring if we were able to sensibly connect the 11.23 and 9.843 day effects. The 1.7 day binary period of Her X-1 and its 35 day variation (usually ascribed to accretion disk

precession of some sort) do, in fact, result in "dips" at their beat period of 1.6 days. An analogous situation here would require a disk precession period of ∿ 80 days (which timescale is not indicated in the ASM data). In view of the imprecise understanding of the 35 day effect in Her X-1 which still remains, even after the detailed scrutiny to which it has been subjected (c.f. Boynton, Crosa and Deeter 1978), it is not at all clear that 11.23 days could not be the "precession" period. Similarly, a third body cannot be excluded. A binary period as large as 9.843 days would be less likely to yield significant X-ray photometric modulation than would a shorter period, in which case the absence of a direct connection between 11.23 days and 9.843 days is disappointing, but not necessarily surprising. The final confirmation of either 9.843 or 11.23 days with a binary period <u>would</u> be disappointing (at least to these authors), since it would virtually demand that the degenerate object in the system be a neutron star. The apparent success in applying the spectral modelling of Kylafis et al. (1979) to Cyg X-2 with the assumption of a degenerate <u>dwarf</u> as the compact object represents a significant new step in the utilization of X-ray spectra (and spectral-temporal correlations) for the inference of fundamental source parameters; it would indeed be unfortunate if Cyg X-2, which appears to be prototypical of a degenerate dwarf in all respects vis-a-vis the Kylafis et al. model, turns out to be a neutron star instead.

c. Cyg X-3

The 4.8-hour modulation of Cyg X-3 is at the high-frequency limit of the ASM data capability. We find that the parameters which characterize

the shape of the modulation (epoch of minimum, phase of maximum and ratio of maximum to minimum intensity) are independent (typically to $\lesssim$ 10%) of the local source intensity. This modulation is ascribed to the binary period of a neutron star in the stellar wind of its companion (c.f. Becker et al. 1978) or embedded in an optically thick shell (c.f. Milgrom 1976). Becker et al. have detected a marked phase dependence in the spectra of two relatively low intensity episodes of Cyg X-3, which is manifested most obviously in precisely the 3-6 keV energy band to which the ASM is sensitive. In both of the two Becker et al. measurements, the maximum-to-minimum ratios were systematically higher by $\sim$ 5% in the band 3-6 keV than in the band 6-20 keV (although the 6-20 keV ratios of the two differed from each other by a like percentage).

The low-average trace of Figure 4 yields a ratio of 2.22 $\pm$ .30 which, although it should represent a lower limit by virtue of the sampling systematics of the ASM, agrees well with the Becker et al. values of $\sim$ 2.1 and $\sim$ 1.9. The high-average trace yields 1.75 $\pm$ .13 and, while consistent with the overall trace value of 1.87 $\pm$ .14, is suggestive of a decreasing ratio with increasing intensity. Serlemitsos et al. (1975) have pointed out that the <u>total</u> X-ray luminosity of Cyg X-3 is independent of high-or-low state, as the spectrum (at like 4.8-hour phase) apparently changes from power-law to blackbody with increasing observed intensity with the luminosity unaffected (in fact, the luminosity is inferred to be close to Eddington-limited). The present result is consistent with the picture of a hard X-ray source which becomes more optically thick (via electron scattering) with increasing intensity, as

the maximum-to-minimum ratio of the 4.8-hour modulation certainly does not markedly increase with increasing intensity.

The precise 4.8-hour period value we have chosen to fold the data over is that of Parsignault et al. (1976). Our data record cannot statistically exclude either the Parsignault et al. period with $\dot{P}$ = 0, the Copernicus period with $\dot{P} = 0$ (Mason, Sanford and Ives 1976), or the newly proposed COS-B value with $\dot{P} \neq 0$ (Manzo, Molteni and Robba 1978).

The 16.75-d period we previously reported (Holt et al. 1976d) does not appear to persist through the entire 1300-d data base. If any such long-term periodicity is present, it is more likely to be 33.0 $\pm$ .2-d with two peaks separated by 1/3 of the period. A host of exotic possibilities arise if such modulation can be confirmed (e.g. an eccentric orbit has two points of closest approach to a focus which differ by less than half the orbital period, in which case the 4.8-hour modulation might be reexamined for a rotational origin), but our data do not demand its reality.

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FIGURE CAPTIONS

Figure 1 - Raw 1300 day histories of Cyg X-1, Cyg X-2, and Cyg X-3. Each data point represents an average intensity over 5.6 days. There are some obvious systematic increases which occur simultaneously in two or all three sources. See text for an explanation of how the data were accepted for further analysis.

Figure 2 - The total Cyg X-1 record, less the data in the two unambiguous high states, folded modulo 5.6 (ephemeris of Bolton 1975) and 78.4 (ephemeris of Kemp, Herman and Barbour 1978) days. The solid traces represent the separate light curves for episodes where the average source intensity was relatively high or relatively low (see text). The dashed traces are the light curves for all of the data. The inset exhibits the lack of χ^2 "signal", which would have a shape similar to the dashed triangular trace if a 78.4 day periodicity was detectable in our data.

Figure 3 - Cygnus X-2 data. The upper trace is an autocorrellagram with one-day lags (see text); the arrows represent the locations of expected features for an 11.23-day period. The lower trace is all the data folded modulo 11.23 days. The inset is the distribution of the χ^2 obtained, as a function of trial period, for folds similar to the lower trace against the hypothesis of a constant source intensity. The epoch of minimum for a sinusoidal fit to the lower trace midway through our data sample is JD2,443,000.9.

Figure 4 - Cyg X-3 data folded modulo the 4.8-hour period of Parsignault et al. (1976). The dashed trace includes all the data, while the solid traces are the separate folds for relatively high and relatively low average source intensities. The center of bin 1 corresponds to the minimum epoch of Mason, Sanford and Ives (1976). As described in the text, each measurement is typically accumulated over $\sim$ 5 bins, but is added to only that bin which corresponds to the midpoint of that measurement.

Figure 5 - Cygnus X-3. The light curves, autocorrellagram and χ^2 distribution are as described in previous captions. The arrows represent the positions in the autocorrellagram where features are expected for a 33-day modulation with two peaks separated by 10 days. The epoch for the start of the light curve trace, midway through our data sample, is JD2,442,987.5.

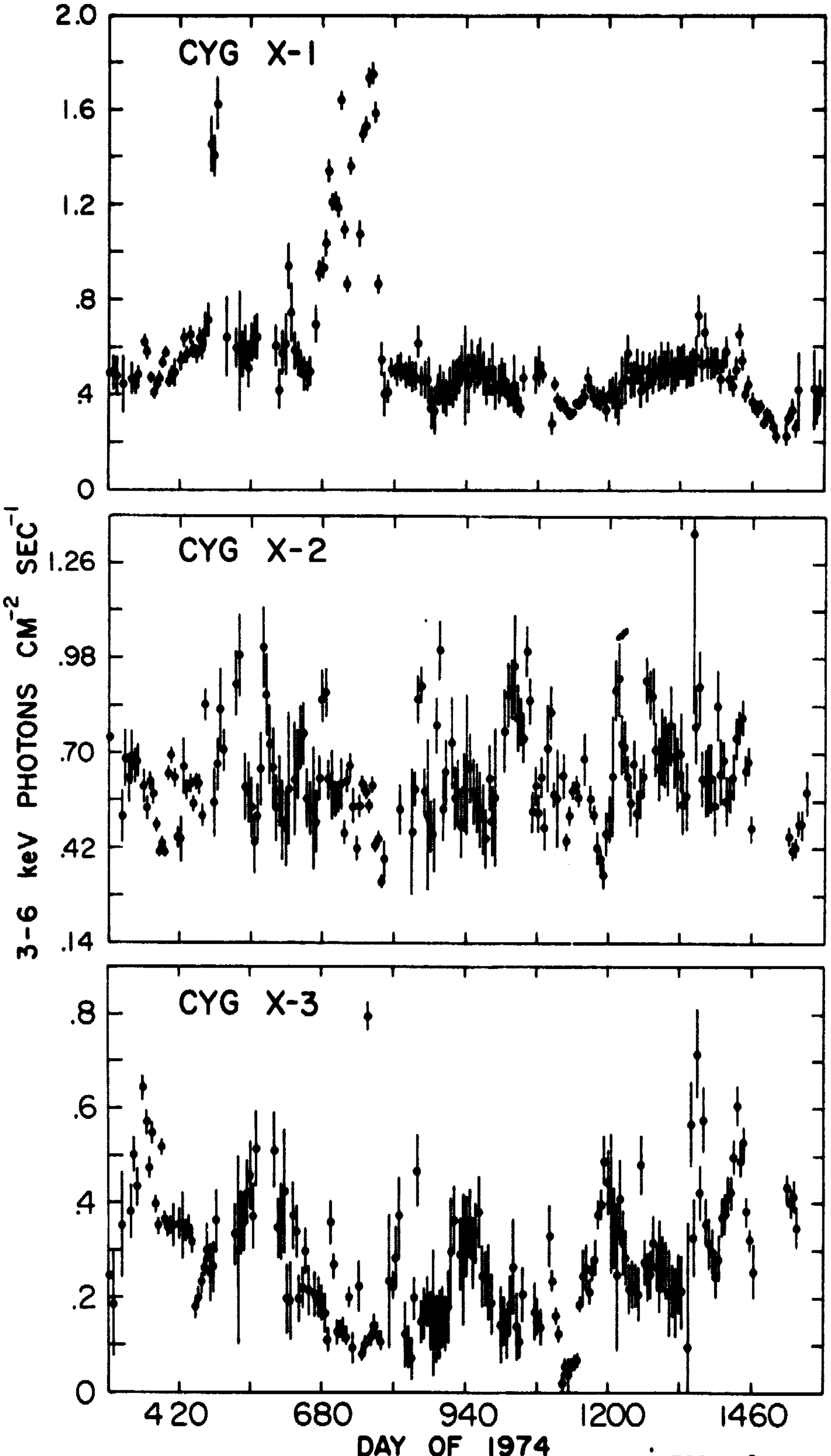
CYG X-1
CYG X-2
CYG X-3
3-6 keV PHOTONS CM^{-2} SEC^{-1}
2.0
1.6
1.2
.8
.4
0
1.26
.98
.70
.42
.14
.8
.6
.4
.2
0
420
680
940
1200
1460
DAY OF 1974

FIG. 1

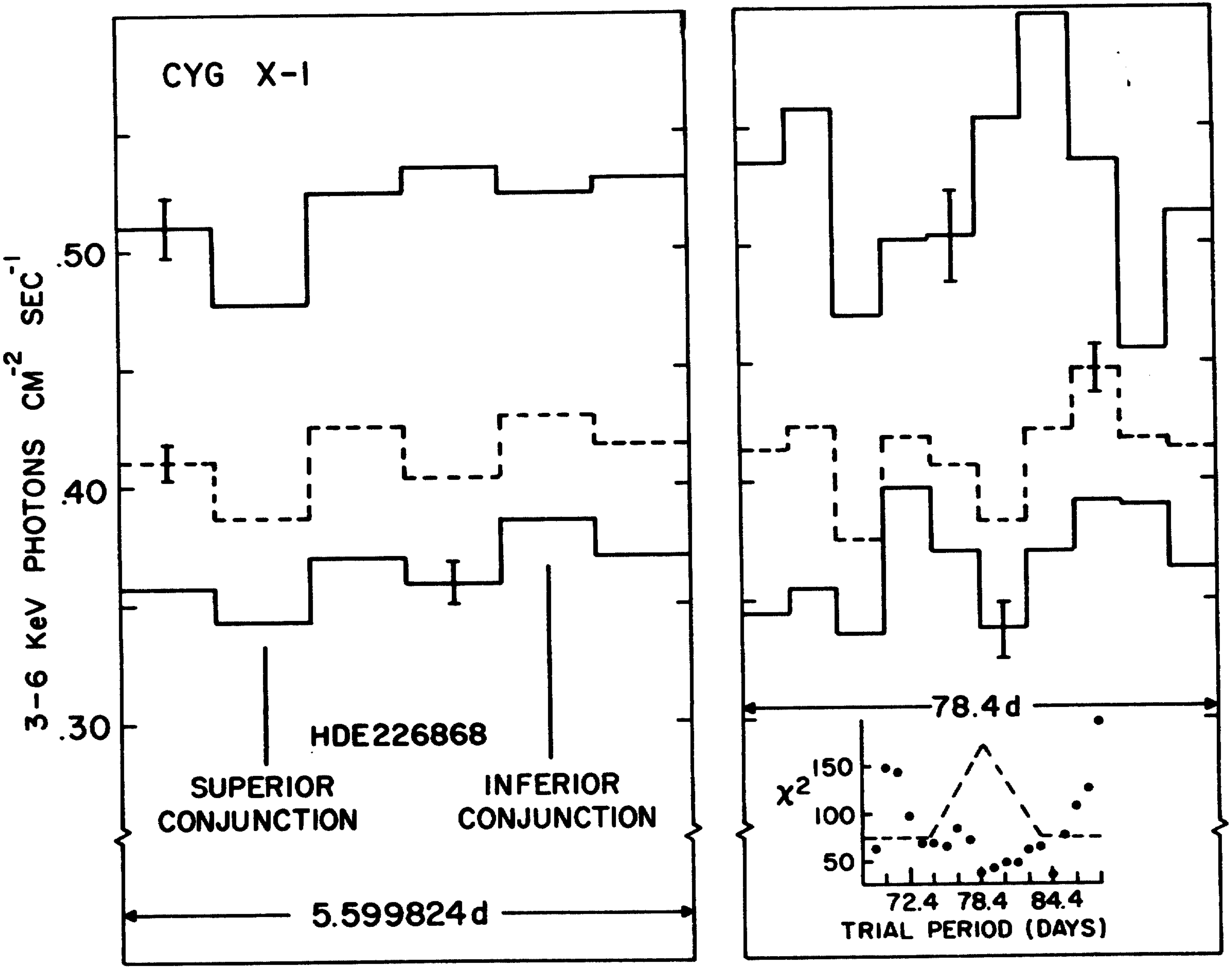
CYG X-1
3-6 KeV PHOTONS CM^-2 SEC^-1
.50
.40
.30
HDE226868
SUPERIOR CONJUNCTION
INFERIOR CONJUNCTION
5.599824d
78.4d
χ²
150
100
50
72.4 78.4 84.4
TRIAL PERIOD (DAYS)

FIG. 2

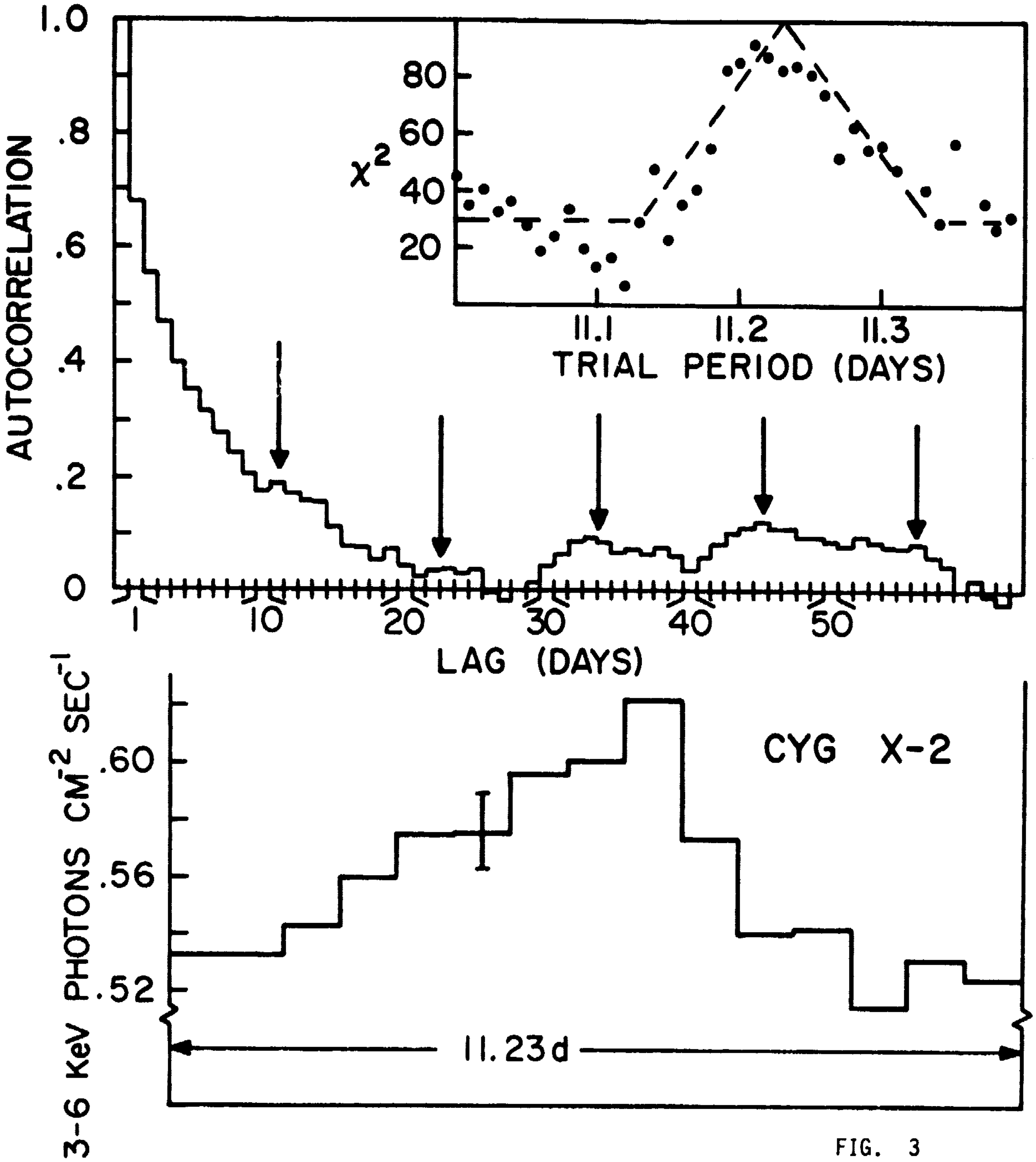
1.0
.8
.6
.4
.2
0
AUTOCORRELATION
80
60
40
20
χ^2
11.1
11.2
11.3
TRIAL PERIOD (DAYS)
1
10
20
30
40
50
LAG (DAYS)
.60
.56
.52
3-6 KeV PHOTONS CM^{-2} SEC^{-1}
CYG X-2
11.23d

FIG. 3

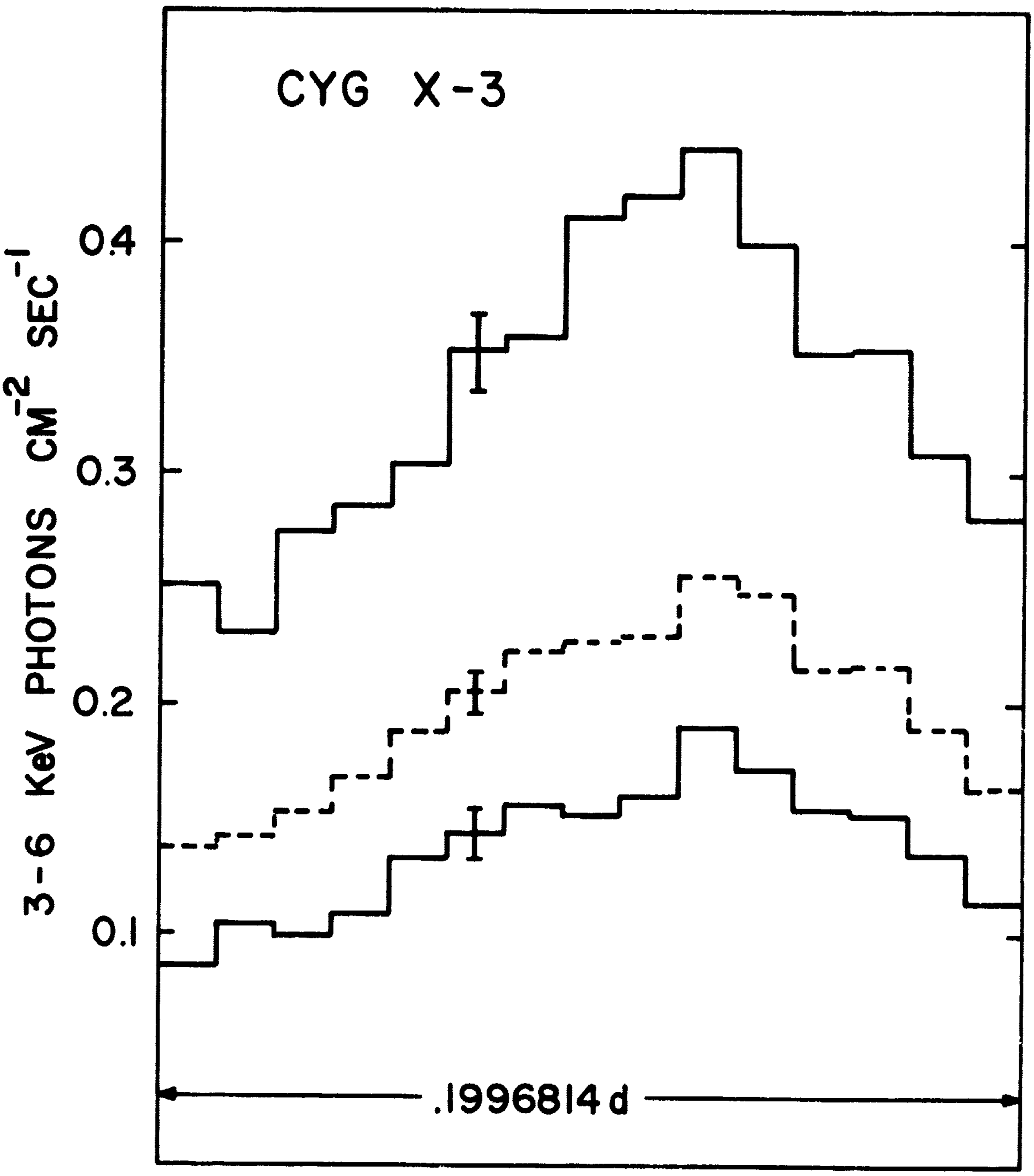

FIG. 4

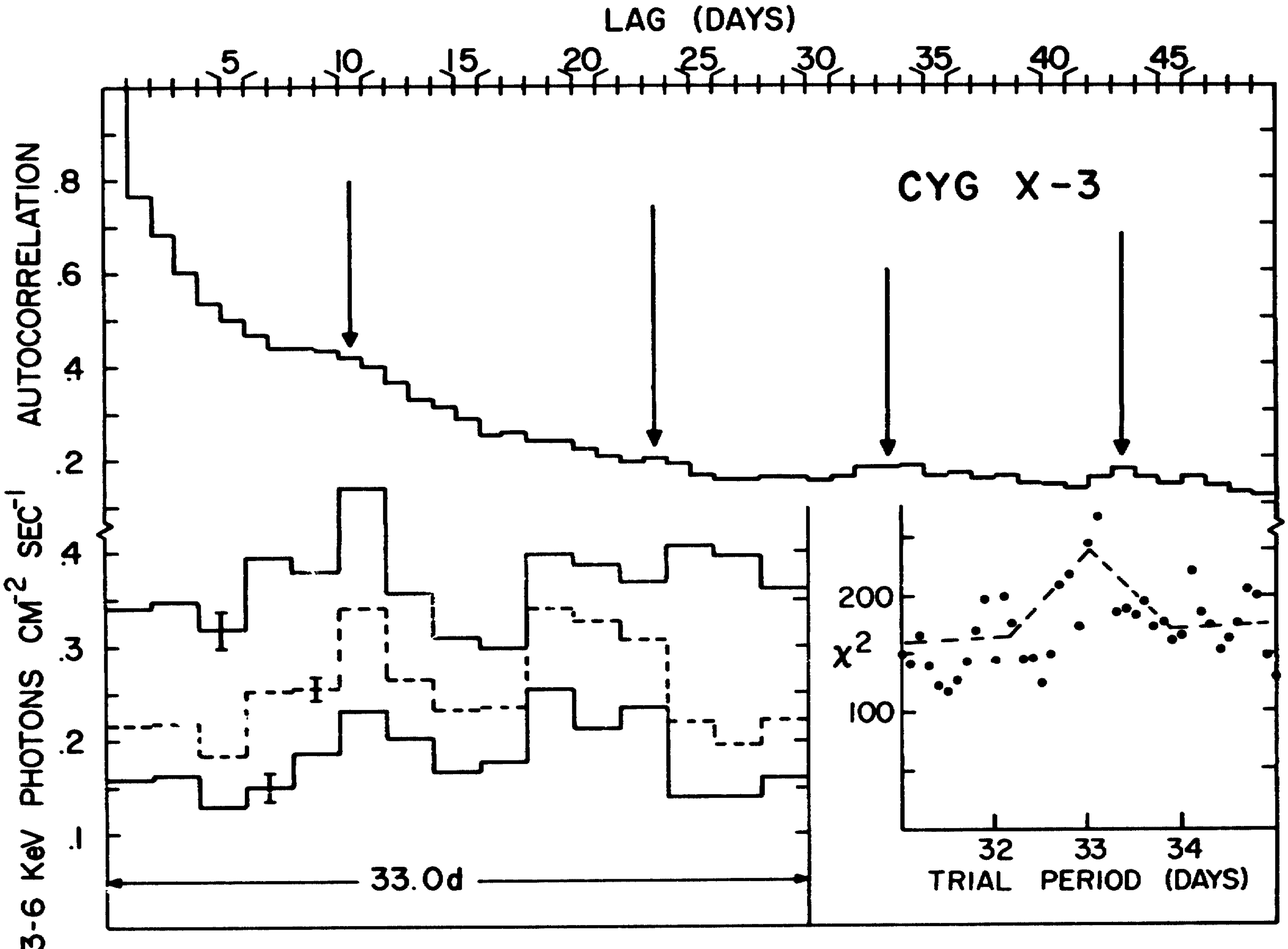
LAG (DAYS)
5
10
15
20
25
30
35
40
45
AUTOCORRELATION
.8
.6
.4
.2
3-6 KeV PHOTONS CM^{-2} SEC^{-1}
.4
.3
.2
.1
CYG X-3
33.0d
200
χ^2
100
32
33
34
TRIAL PERIOD (DAYS)

FIG. 5